Using an active sensor to make in-season nitrogen recommendations for corn

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Abstract

An active crop canopy reflectance sensor could increase N-use efficiency in corn (*Zea mays* L.), if temporal and spatial variability in soil N availability and plant demand are adequately accounted for with an in-season application. Our objective was to evaluate the success of using an active sensor for making N recommendations to corn. Seven increments of in-season N fertiliser (0 to 280 kg/ha) were applied to corn at each of 15 sites during two years. These sites were selected to represent the corn production regions of east central and southeastern Pennsylvania, conditions typical in the USA mid-Atlantic region. Canopy reflectance in the 590 nm and 880 nm wavelengths, soil samples, and above-ground biomass were collected at the 6^{th}-7^{th}-leaf growth stage (V6-V7). Relative Green Normalised Difference Vegetation Index ($GNDVI_{relative}$) was determined, as GNDVI(0N) / GNDVI(280 kg N/ha applied at planting). Grain yield was determined at harvest. Economic Optimum N Rate (EONR) was determined using a quadratic-plateau yield response function. Observations from the current study were compared to relationships between EONR and $GNDVI_{relative}$ or the presidedress NO_3 test (PSNT) that were developed in an earlier study, based on an absolute mean difference (AMD) between observed EONR and the previously determined predicted relationships. The AMD for the EONR and $GNDVI_{relative}$ relationship from the current study was 62.9 kg N/ha. The same measure of AMD was 75.0 kg N/ha for the relationship between EONR and PSNT. $GNDVI_{relative}$ captured similar information as the PSNT, as reflected in a strong relationship (R^2=0.57) between these two measurements. Above-ground biomass at V6-V7 was correlated with PSNT (R^2=0.38), and $GNDVI_{relative}$ was dependent on above-ground biomass (R^2=0.51). While the PSNT has been considered one of the best methods for making N recommendations to corn in Pennsylvania, $GNDVI_{relative}$ provided as good or better an indicator of EONR as PSNT, and provides an opportunity to easily adjust in-season N applications spatially.

Keywords: remote sensing, precision agriculture, spatial variability

Introduction

As the world population approaches seven billion, corn production without the adverse environmental impacts of N fertiliser will be essential to sustainable agriculture. One of the major challenges related to corn (*Zea mays* L) production today is the adverse environmental impacts associated with the large amounts of N fertiliser applied to this crop. Nitrogen fertiliser recovered in the above-ground plant biomass is less than 40% of the amount applied in the same year as the crop grown, as represented by the major corn producing areas of the United States (Cassman *et al.*, 2002). Nitrogen fertiliser in excess of the amount required by corn is readily leached through soil as NO_3 and adversely impacts ground and surface waters (Hong *et al.*, 2007). With elevated NO_3

levels in ground and surface waters, human health risks are increased and premature eutrophication of surface waters contributes to a cascade of negative impacts on aquatic life, fishing and tourist industries, and drinking water quality.

After the 1940's when the availability of N fertiliser increased dramatically through the Haber-Bosch process, N fertiliser recommendations were developed to facilitate the appropriate use by farmers of this new and cheap source of N fertiliser. Many N fertiliser recommendations in the USA were developed based on a model in which yield goal was the defining independent variable. While some states still rely on this approach (Buchholz *et al.,* 1993; Shapiro *et al.,* 2003; Beegle, 2008), there has been a recent move towards developing N recommendations that better reflect economic return (Sawyer *et al.,* 2006). Maximum yield, i.e. yield goal, does not usually correspond well with the economic optimum N rate (EONR; Fox and Piekielek, 1995; Vanotti and Bundy 1994), and EONR represents best return for the farmer and corresponds with minimal N losses to the environment (Hong *et al.,* 2007).

While the spatial variability in crop demand and soil supplying capacity for nutrients has long been recognised, the recent availability of precision technologies has encouraged researchers to pursue methods with which to capture the appropriate information for spatially variable N recommendations (Blackmer *et al.,* 1995; Scharf *et al.,* 2005; Schmidt *et al.,* 2007). Remote sensing techniques can be used to detect N deficiency in corn (Blackmer *et al.,* 1995), and the density of spatial information available using this technology is particularly attractive for developing spatially variable N recommendations. Active sensors that can be mounted on a N applicator are commercially available, and recent research suggests that these sensors can be used for developing N recommendations for corn (Dellinger *et al.,* 2008). While this latest research has correlated EONR directly to canopy reflectance, the results were based on field studies from a relatively small geographic region, and whether the developed algorithms can be extrapolated to a larger geographic region was undetermined.

The objective of the current study was to evaluate the relationship between EONR and crop canopy reflectance for 15 different field site – years in Pennsylvania, USA.

Materials and methods

Corn was grown in a total of 15 farmers' fields in 2007 and 2008, located in east central and southeastern Pennsylvania (Table 1). Previous crop at each of these sites was either corn or soybean (*Glycine Max* L. Merr.) with notill (i.e. no tillage) the standard tillage practice. Except for N fertiliser application, local management practices typical for corn production were followed.

At each site, eight N treatments were arranged in a randomised complete block design with four blocks. Nitrogen treatments included: 0 (control), 45, 90, 135, 180, 225, and 280 kg N/ha applied at V6-V7 growth stage (6^{th}-7^{th} fully mature leaf); and 280 kg N/ha applied immediately after planting (N reference). These treatments were adjusted slightly at one site, PC3-2007, because the farmer had inadvertently applied 45 kg N/ha at planting, so additionally including: 0, 22, 45, 67, 135, 180, and 225 applied at V6-V7; and 280 kg N/ha applied immediately after planting. Nitrogen was broadcast applied by hand between the rows as NH_4NO_3 in 2007 and as urea in 2008. Plots were 4.6-m wide by 9.1 m long (six 0.76 m wide rows).

Preplant soil samples consisted of four or five 10-cm-diam. cores (open-faced auger), 0-15 cm deep, collected at planting. Samples from all four blocks were composited and a subsample retained, air dried, and ground to pass a 2-mm sieve. Soil pH, P, K, and organic matter content were determined by the AASL (http://www.aasl.psu.edu). Details about specific analytical methods were provided by Dellinger *et al.* (2008).

Soil samples for the presidedress NO_3 test (PSNT) were collected at V6-V7 from each control treatment (n=4). Samples consisted of two or six 10 or 2 cm diam. cores (open faced-auger or

Table 1. Geographic location and selected soil characteristics for each field site.

Year	Geographic location		Previous	Dominant soil type[a]	Initial soil characteristics, 0-15 cm depth					
Site	North	West	crop		OM[b] content g/kg	pH mg/kg	M3-P[c] mg/kg	M3-K mg/kg	NO_3-N mg/kg	NH_4-N mg/kg
2007										
PC1	40°49'33'	77°05'18'	Soybean	Berks shaly silt loam	3.0	7.1	25	149	7.9	3.3
PC2	40°49'22'	77°06'32'	Soybean	Shelmadine silt loam	2.4	6.9	75	101	11.1	7.4
PC3	40°51'12'	77°03'46'	Soybean	Alvira silt loam	2.6	6.9	34	117	3.3	1.7
K1	40°42'03'	76°34'17'	Corn	Basher silt loam	2.2	4.9	82	76	4.4	3.7
K2	40°42'14'	76°34'09'	Corn	Leck kill channery silt loam	3.1	7.2	220	186	4.7	4.1
2008										
PC1	40°49'21'	77°04'38'	Soybean	Hartleton channery silt loam	2.8	6.2	103	163	10.4	3.9
S1	40°49'00'	76°52'35'	Corn	Monongahala silt loam	1.7	6.2	99	106	5.5	3.3
S2	40°49'07'	76°52'24'	Corn	Monongahala silt loam	2.1	6.7	87	107	7.3	4.4
K1	40°42'13'	76°33'53'	Corn	Atkins silt loam	1.7	7.2	39	77	11.3	6.9
K2	40°42'20'	76°33'52'	Corn	Meckesville loam	2.3	5.4	37	56	9.9	9.1
MJ1	40°09'07'	76°30'04'	Corn	Bedington silt loam	3.5	6.5	576	264	15.2	2.8
MJ2	40°05'07'	76°32'39'	Soybean	Duffield silt loam	2.4	6.6	365	364	19.4	2.4
L1	40°06'47'	76°15'18'	Soybean	Hagerstown silt loam	2.9	7.1	440	331	5.3	2.6
L2	40°07'13'	76°25'27'	Soybean	Hagerstown silt loam	2.4	6.9	137	264	7.4	2.6
L3	40°07'12'	76°25'28'	Corn	Duffield silt loam	2.2	6.4	62	104	5.5	4.5

[a] USDA-NRCS soil survey (http://websoilsurvey.nrcs.usda.gov/app/WebSoilSurvey.aspx).

[b] OM = organic matter.

[c] Phosphorus and K were determined using the Mechlich-3 method and an indcutively coupled plasma spectrophotometer (ICP).

step tube-type probe, respectively) from 0-30 cm deep. A subsample was retained, air dried, and ground to pass a 2 mm sieve.

To determine inorganic soil N, ten g of soil were shaken in an Erlenmeyer flask with 50 ml of 2 M KCl for 30 minutes at 200 rpm, filtered through a Whatman No. 2 filter paper, and analysed for NH_4-N and NO_3-N using flow injection analysis (QuickChem Method 10-107-04-1-A, Lachat Instruments, Milwaukee, WI).

Canopy reflectance data were collected at V6-V7 (≈ 16-30 June) using a Crop Circle ACS-210 sensor (Holland Scientific, Lincoln, NE). The ACS-210 measures reflectance at 590 (VIS_{590}) and 880 (NIR_{880}) nm from light emitted by a modulated polychromatic Light Emitting Diode (LED) array, so is considered an 'active' sensor. The sensor was carried on a pole approximately 60 cm above and perpendicular to the corn leaf canopy. Reflectance was measured from one row in each plot (row three of six rows), providing ≈ 40 measurements per plot. A Trimble Pro XRS Global Positioning System (GPS) receiver (Trimble Navigation Limited, Sunnyvale, CA) and Trimble TSCe field computer (Trimble Navigation Limited, Sunnyvale, CA) were used to simultaneously record the location of each reflectance measurement. All reflectance measurements outside a 1 m buffer inside the plot boundary were discarded, and the mean reflectance ($n \approx 40$) was assigned to each plot. The green normalised difference vegetation index (GNDVI) was determined for each plot based on Equation 1 (Dellinger *et al.,* 2008).

$$GNDVI = \frac{NIR_{880} - VIS_{590}}{NIR_{880} + VIS_{590}} \tag{1}$$

Relative GNDVI for each field site was determined based on the means ($n = 4$) of the control and reference (280 kg N/ha) treatments (Equation 2).

$$GNDVI_{relative} = \frac{GNDVI_{control}}{GNDVI_{reference}} \tag{2}$$

Plant biomass was determined for the control and N reference treatments at V6-V7 by clipping the above-ground biomass of a 2-m length of row from rows one or six of the six-row plot. Samples were dried at 70 °C and weighed. Relative biomass was determined similarly to $GNDVI_{relative}$ (Equation 2), dividing biomass from the control by biomass from the N reference.

Grain yield was determined based on the entire length (9.1 m) of the middle two rows in each plot; hand harvested, shelled, and weighed. Yield was adjusted to 155 g/kg moisture content. Estimates of corn ($ 157.28/mg or $ 4.00/bu) and fertiliser ($ 1.32/kg or $ 0.60/lb) prices were used with the quadratic-plateau yield response functions to calculate the economic return to N fertiliser as a function of N fertiliser rate for each field site. The EONR was determined as the N rate corresponding to maximum return based on these prices. If a quadratic-plateau yield response was not statistically significant (α=0.05), the mean yield for each increasing split plot N treatment was compared to the mean yield for all greater split plot N treatments. This comparison of mean yields continued with each increasing split plot N treatment until a significant difference was not detected. The smallest split plot N treatment in this final comparison was selected as the EONR (Sripada *et al.,* 2008).

PROC NLIN or PROC REG (SAS Institute Inc., Cary, NC) were used to fit a split-line, linear-plateau, and quadratic-plateau or linear regressions, respectively, for EONR as a function of various independent variables, including: grain yield, $GNDVI_{relative}$, relative biomass, or PSNT. The R^2 for the split-line, linear-plateau, and quadratic-plateau regressions were determined as the r^2 for a linear regression between predicted vs. observed values.

The success of using $GNDVI_{relative}$ or PSNT in estimating EONR from the current study was based on a comparison to the algorithms for the same relationships developed from an earlier study (Dellinger *et al.,* 2008), using the absolute mean difference (AMD) between EONR observed in the current study and previously determined predicted relationships. Details of the previous study are provided by Dellinger *et al.* (2008), but a brief description is provided here.

Similar N treatments and methods as already described in the current were used in the earlier study to determine EONR and $GNDVI_{relative}$. The treatments described in the current study were split plot treatments in the earlier study, and whole plot treatments included a control of 0 kg N/ha, 56 kg N/ha as NH_4NO_3, and 37-122 kg/ha of available N (range among fields) as dairy manure, all applied within 7 days before planting. The earlier study included eight sites in two years within a small geographic region (<20 k distance; Centre County, Pennsylvania). The previous crop varied among sites, including corn, soybean, or alfalfa (*Medicago sativa* L.). The combination of varied previous crops and whole plot treatments provided a broad range of EONRs (n=24) from which to develop relationships with $GNDVI_{relative}$ or PSNT. All sampling methods were similar between studies.

Results and discussion

Without preplant fertilizer or when manure was applied before planting, EONR was strongly related to $GNDVI_{relative}$ (R^2=0.84) in a split-line type relationship, decreasing from 174 kg N/ha to almost zero as $GNDVI_{relative}$ increased from 0.85 to 1.0 (Dellinger *et al.*, 2008). Using the same data and including the third preplant treatment (56 kg N/ha) in the regression analysis, the relationship between EONR and $GNDVI_{relative}$ was still strong (R^2=0.76, Figure 1a). These results, while encouraging and representing a broad range of management practices (Dellinger *et al.*, 2008), represented a relatively small geographic region; so the current study focused on extending this work to other corn producing regions of Pennsylvania, USA.

The dominant soil types for each of the 15 sites selected in farmers' fields from east central and southeastern Pennsylvania included various loams and silt loams (Table 1). General soil characteristics reflected typical conditions of the corn producing regions of Pennsylvania. Soil OM content ranged from 1.7 to 3.5 g/kg; pH from 4.9 to 7.2; soil test P from 25 to 576 mg/kg; and soil test K from 56 to 364 mg/kg (Table 1). Preplant inorganic NO_3 and NH_4 was between 3.3 and 19.4 mg NO_3-N/kg and 1.7 and 7.4 mg NH_4-N/kg. While the soil characteristics were sometimes less

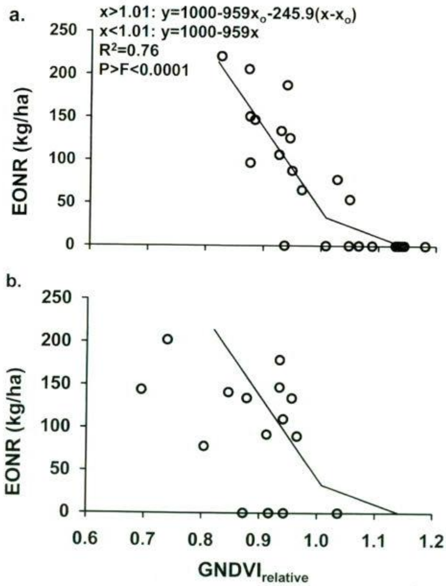

Figure 1. Economic optimum N rate (EONR) as a function of relative Green Normalised Difference Vegetative Index ($GNDVI_{relative}$) for the (a) previous and (b) current study.

than optimum (e.g. soil pH=4.9 or soil test P=25 mg/kg), these farmers' fields provided realistic conditions for testing these technologies.

Because there were fewer field sites in the current study where EONR=0, fitting a split-line regression for the relationship between EONR and $GNDVI_{relative}$ was not possible. However, a comparison to the relationship developed in the earlier study (Figure 1a) was possible. The measure of success was based on the difference between the observed EONR in the current study and the predicted EONR of the earlier study. The absolute mean difference (AMD) between the predicted and observed EONR in the earlier study was 23.9 kg N/ha (Figure 1a). This represents a good relationship and is comparable to the best indicator (i.e. the PSNT) currently available for making N recommendations for corn (Figure 2a; Schmidt *et al.,* in press). The AMD between observed EONR from the current study and the earlier study's predicted EONR (Figure 1b) was 62.9 kg N/ha, 39 kg N/ha greater for these fields representing a larger geographic region in Pennsylvania. This measure of deviation was constrained with an upper threshold of 220 kg N/ha for predicted EONR. This constraint, regardless of the value for $GNDVI_{relative}$, confines the sidedress N application to less than 220 kg N/ha. Although there was a 2.5-fold increase in the AMD when results from the larger geographic region (Figure 2b) were compared to predicted EONR from the earlier study (Figure 1a), there was a comparable increase in AMD between results from the two studies for the relationship between EONR and PSNT.

In the earlier study, PSNT was as good an indicator of EONR (R^2=0.78; Figure 2a) as any of the current methods for making N recommendations for corn in Pennsylvania (Schmidt *et al.,* in press), and $GNDVI_{relative}$ was comparably effective (R^2=0.76, Figure 1a). To determine whether PSNT performed as well as an indicator for EONR in the current study as the earlier study, AMD between the predicted and observed EONR was evaluated similarly as with $GNDVI_{relative}$. The AMD increased from 23.1 kg N/ha for the earlier study (Figure 2a) to 75.0 kg N/ha for the current study (Figure 2b). This represents a greater than 3-fold increase in AMD, suggesting that $GNDVI_{relative}$ performed (AMD=62.9 kg N/ha) as well as or better in the current study than one of the best methods

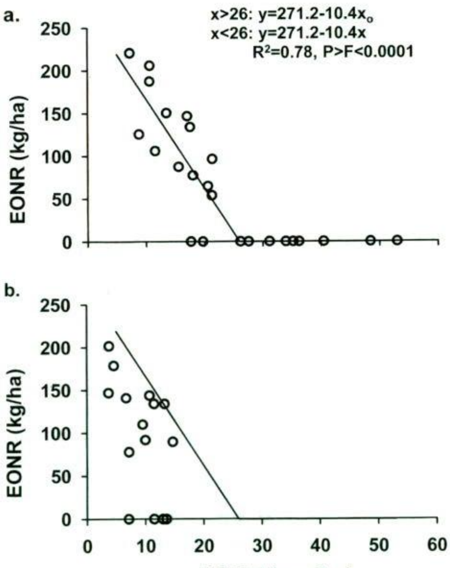

Figure 2. Economic optimum N rate (EONR) as a function of the Presidedress NO_3 test (PSNT) for the (a) previous and (b) current study.

for making N recommendation for corn, PSNT. Reflectance obtained at V6-V7, as $GNDVI_{relative}$, was an effective indicator for EONR and provides a greater opportunity to address spatial and temporal requirements in N availability than using a soil test such as the PSNT.

The success in using $GNDVI_{relative}$ as an indicator for EONR depends on whether the reflectance information obtained at V6-V7 corresponds with corn N requirements for the entire growing season. The advantage to using an in-season indicator such as reflectance obtained at V6-V7 is that the plant behaves as an integrator of conditions and stresses already experienced during the early growing season. If N stress is already present, then $GNDVI_{relative}$ should be an indicator for EONR. Conversely, the shortcoming of obtaining reflectance from corn at V6-V7 is that this growth stage occurs at the beginning of rapid N uptake, so N stresses that occur later in the growing season may not yet be expressed. In the current study, $GNDVI_{relative}$ was related to relative biomass at V6-V7, increasing linearly from 0.74 to 0.93 as relative biomass increased from 0.30 to 0.52 (R^2=0.51, Figure 3). For relative biomass >0.52, $GNDVI_{relative}$ remained constant at 0.93. While not as strongly related (R^2=0.38, Figure 4), relative biomass increased linearly from 0.45 to 0.77 as PSNT increased from 5 to 15 mg/kg. The former relationship indicates that $GNDVI_{relative}$ was a good indicator of relative biomass in the current study. This relationship and the relationship between relative biomass and PSNT suggest that $GNDVI_{relative}$ at V6-V7 is providing similar information as obtained with a PSNT. Combining data from the previous and current studies, $GNDVI_{relative}$ was related to PSNT in a linear-plateau type relationship (R^2=0.57, Figure 5). $GNDVI_{relative}$ increased linearly from 0.8 to 1.1 as PSNT increased from 0 to 31 mg/kg, then $GNDVI_{relative}$ remained constant at 1.1 with PSNT >31 mg/kg. These relationships (Figures 3-5) suggest that crop growth at V6-V7, as measured by

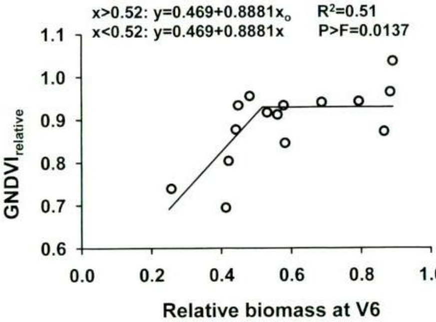

Figure 3. Relative Green Normalised Difference Vegetative Index ($GNDVI_{relative}$) as a function of relative biomass at V6 (current study).

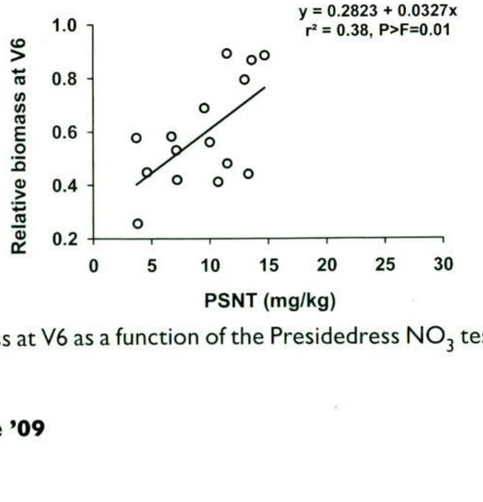

Figure 4. Relative biomass at V6 as a function of the Presidedress NO_3 test (PSNT; current study).

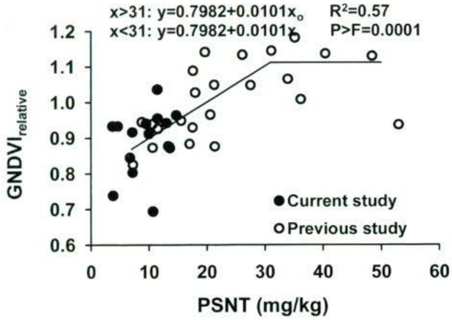

Figure 5. Relative Green Normalised Difference Vegetative Index ($GNDVI_{relative}$) as a function of the Presidedress NO_3 test (PSNT) for data from the previous and current study. The lower-right outlier was omitted from the regression.

$GNDVI_{relative}$, provided similar information as obtained with a PSNT. Based on results from the previous and current studies (Figures 1 and 2), both measurements, $GNDVI_{relative}$ and PSNT, were comparable indicators of EONR.

Conclusion

The current study extended the evaluation of using crop canopy reflectance as an indicator for EONR from Centre County Pennsylvania to 15 additional famers' fields in east central and southeastern Pennsylvania. When compared to the success of PSNT, currently one of the best tools for making N recommendations for corn in Pennsylvania, $GNDVI_{relative}$ obtained at the V6-V7 growth stage was just as effective as PSNT as an indicator of EONR. Determining a N recommendation simultaneously with a sidedress N application using $GNDVI_{relative}$ provides the opportunity to adjust the N application spatially depending on the relative plant demands and soil N availability.

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